INTERSTELLAR DUST MODULE FOR THE ESA METEOROID MODEL

M. Landgraf[1], R. Jehn[1], N. Altobelli[1], V. Dikarev[2], and E. Grün[2]

[1]*ESA/ESOC, Robert-Bosch-Str. 5, 64293 Darmstadt, Germany*
[2]*MPI-K, Postfach 103980, 69029 Heidelberg, Germany*

ABSTRACT

The ESA meteoroid model predicts impacts of meteoroids in the mass range between 10^{-18} to 10^0 g on spacecraft surfaces. It covers heliocentric distances from 0.3 to 20 AU. Measurements of the dust detector on board the highly successful joint ESA/NASA mission Ulysses have shown, that the flux of meteoroids with masses between 10^{-15} and 10^{-12} g is, at least in the outer Solar System, dominated by interstellar dust grains that traverse the Solar System as it travels through the local interstellar cloud. We present a simple semi-analytic interstellar dust model that can easily be included in the ESA meteoroid model, together with a more precise determination of the flux direction of the interstellar dust stream. The model is based on the assumption that interstellar dust dynamics have two effects: solar gravitation and radiation pressure determines the spatial distribution, and Lorentz-interaction of the charged particles creates a temporal variation.

1. INTRODUCTION

As meteoroid impacts are a concern for highly sensitive instruments on board Earth orbiting satellites as well as interplanetary exploration probes, ESA has decided to develop a standard tool for the prediction of impact fluxes. In its first release version the tool (Staubach *et al.* , 1997) has been used to predict meteoroid impact rates in order to assess its contribution relative to the small debris population in Earth orbit. Due to the increase of data available from the in situ measurements of Ulysses and Galileo, as well as from the radar meteor measurements by the AMOR facility in New Zealand, ESA has decided to upgrade the tool. In the course of this update, an extension of the interstellar dust module was proposed.

The former implementation of the ESA meteoroid model includes an interstellar dust component that is modelled as a constant, mono-directional stream of particles moving towards a heliocentric ecliptic direction of $\beta_{\mathrm{ECL}} = -5^o$, $\lambda_{\mathrm{ECL}} = 79^o$, with a flux density (integrated over all grain sizes) of $1.5 \times 10^{-4}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}$ and a velocity of $26\,\mathrm{km\,s}^{-1}$. The direction is identical to the downstream direction of interstellar neutral Helium on its way through the heliosphere (Witte *et al.* , 1993). From the analysis of the Ulysses dust data it was found, that the downstream direction of interstellar dust is statistically indistinguishable from the gas direction (Frisch *et al.* , 1999). The current implementation of the interstellar dust module assumes that the particles move on straight lines through the Solar System. This is a good approximation for particles with masses around $3 \times 10^{-16}\mathrm{kg}$, for which the forces of gravity and radiation pressure nearly cancel each other. The ratio β of radiation pressure to gravity is equal unity for these particles (see figure 1).
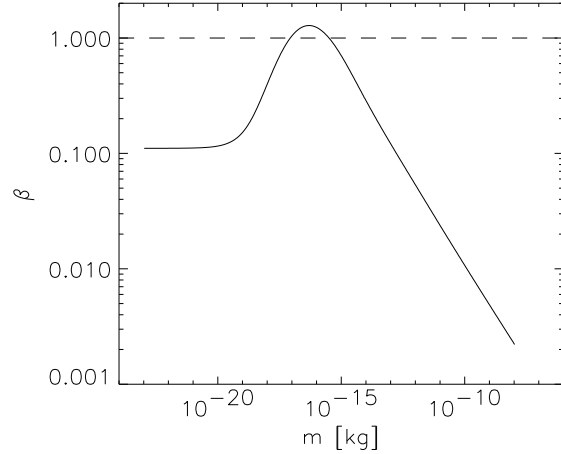

Figure 1. Ratio β of radiation pressure force to gravity on dust grains in the Solar System as a function of grain mass m. The dashed line indicates $\beta = 1$, for which radiation pressure and gravity exactly cancel each other (Gustafson, 1994).

2. SPATIAL DISTRIBUTION OF INTERSTELLAR DUST IN THE SOLAR SYSTEM

For values of β other than unity, the particles move on Kepler hyperbola (figure 2). As a consequence, the apparent stream direction and local concentration depends on the location of the detector in the
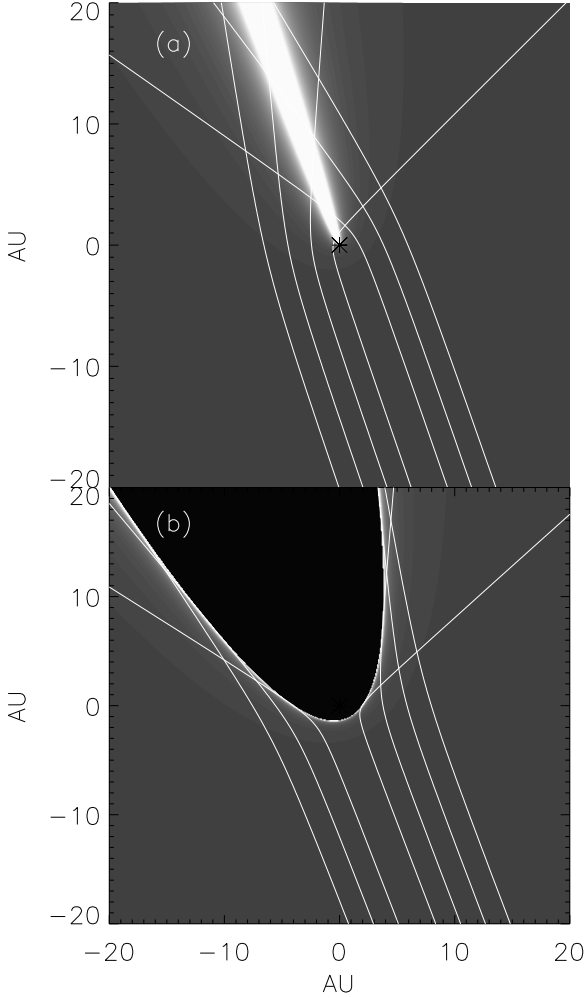
solar system (Landgraf *et al.* , 1999).

Figure 2. *Spatial distribution and motion of interstellar dust grains with $\beta \neq 1$ in a 40×40 AU region around the Sun in the ecliptic plane. The gray-scale contours indicate the spatial concentration and the solid lines show the hyperbolic paths of grains with selected initial conditions. Diagram (a) shows the situation for grains with $\beta = 0.5$, and diagram (b) for grains with $\beta = 1.5$.*

3. TEMPORAL MODULATION OF THE LOCAL INTERSTELLAR FLUX

Ulysses measured a variation of a factor of 3 in the flux of interstellar dust grains in the Solar System (Landgraf *et al.* , 2000). This was attributed to the electromagnetic interaction of the charged grains with the solar wind magnetic field that varies with the 22 year solar cycle (Landgraf, 2000). Interstellar dust grains are charged mainly due to the photo-effect caused by solar UV photons. Because of the magnetic field that is frozen in the radially expanding solar wind (speed between 300 and 700 km s^{-1}),

a Lorentz force acts on the grains. The direction this force depends on the phase of the solar cycle. During the period from 1991 to 2002 it is was directed such that interstellar grains are deflected away from the solar equator. Consequently the local interstellar dust concentration is significantly reduced. While proof of the electromagnetic hypothesis still pending, we employ the model described by Landgraf (2000) to calculate the temporal flux variation for various grain sizes (and thus charge-to-mass ratios). Figure 3 shows the normalised spatial concentration of grains of various sizes as a function of time over one full solar cycle from 1991 to 2013. For flux predictions after 2013 we assume a perfect periodicity of the solar cycle.
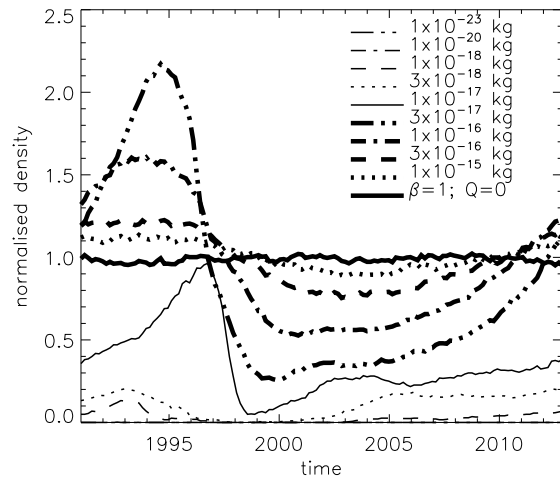

Figure 3. *Temporal variation of the flux of interstellar dust in the solar system (inside 10 AU) over a full 22 year solar cycle for various grain masses. As a reference, grains with $\beta = 1$ and charge $Q = 0$ C are given (thick, solid line) that are effectively not affected by gravity, radiation pressure, and Lorentz-force.*

Because of the differential susceptibility of small and big grains to the electromagnetic deflection described above, the grain mass distribution far from the Sun can not me measured directly inside the solar system. We assume that the grain masses are distributed according to

$$n(m)dm \quad = \quad n_0 m^{-/1.83} dm. \qquad (1)$$

We implement the temporal variation of the dust concentration in the interstellar dust module of the ESA meteoroid model by modulating the grain mass distribution over time.

4. INTERSTELLAR DUST STREAM DIRECTION

The interstellar dust stream direction has been determined from Ulysses data collected within four weeks of the Jupiter fly-by (Frisch *et al.* , 1999). With the now much extended database, a more accurate determination is possible.
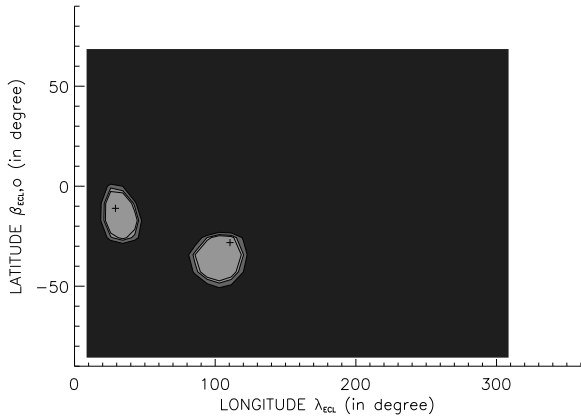

Figure 4. *Best-fit χ^2 analysis of the Ulysses data between Jupiter fly-by and south polar pass. The contour levels (from light to dark) indicate* 10%, 5%, *and* 1% *confidence intervals. Crosses mark local minima of the χ^2 function. The lower right cross represents the global minimum (*99% *confidence level), the second local minimum represents a fit with a* 98% *confidence level.*

Figure 4 shows the fit-levels of an interstellar dust directional model compared with data provided by the Ulysses dust experiment in the time range from the Jupiter fly-by in February 1992 to January 1994, just before the first pass of Ulysses over the south pole of the Sun. For the analysis we use only impacts with a mass (also measured by the detector) between 10^{-14} kg and 10^{-12} kg. For these grains the solar radiation pressure and the gravity of the Sun are equal (figure 1). Thus, it can be assumed that such grains are not deviated from their original direction of motion. Moreover, only impacts, which are the most reliably detected, are used for the comparison with the model. The interstellar dust flow model can be characterised by the vector $(\lambda_{ECL}, \beta_{ECL,0}, \sigma_\beta)$, where λ_{ECL} and $\beta_{ECL,0}$ are respectively the ecliptic longitude and latitude of the dust flow direction, and σ_β the width of the directional distribution. From this model the total number of dust impacts for each spacecraft rotation angle interval is calculated. The expected number of impacts per rotation angle, derived from the model and the measured number of impacts per rotation angle interval have been compared by the χ^2 statistical method. Its minimum, presented in figure 4, gives the model parameters providing the best fit to the data. The best-fit parameters for the main

downstream direction of interstellar dust in the Solar System is heliocentric longitude $\lambda_{ECL} = 110°$ and heliocentric latitude $\beta_{ECL,0} = -30°$. Also a broadening of the directionality by $\sigma_\beta = 20°$ was found to provide the best fit.

It can be seen from figure 4 that the best-fit flow direction of interstellar dust is not determined unambiguously. Another good fit is achieved for $\lambda_{ECL} = 30°$ and $\beta_{ECL,0} = -10°$. Analysis of the Ulysses data is ongoing in order to resolve this ambiguity.

REFERENCES

Frisch, P. C., Dorschner, J., Geiß, J., Greenberg, J. M., Grün, E., Landgraf, M., Hoppe, P., Jones, A. P., Krätschmer, W., Linde, T. J., Morfill, G. E., Reach, W. T., Slavin, J., Svestka, J., Witt, A., & Zank, G. P. 1999. Dust in the Local Interstellar Wind. *Astrophysical Journal*, **525**, 492–516.

Gustafson, B. Å. S. 1994. Physics of Zodiacal Dust. *Annual Review of Earth and Planetary Science*, **22**, 553–595.

Landgraf, M. 2000. Modeling the Motion and Distribution of Interstellar Dust inside the Heliosphere. *Journal of Geophysical Research*, 10,303–10,316.

Landgraf, M., Augustsson, K., Grün, E., & Gustafson, B. Å. S. 1999. Deflection of the Local Interstellar Dust Flow by Solar Radiation Pressure. *Science*, **286**, 2319–2322.

Landgraf, M., Baggaley, W. J., Grün, E., Krüger, H., & Linkert, G. 2000. Aspects of the Mass Distribution of Interstellar Dust Grains in the Solar System from In-Situ Measurements. *Journal of Geophysical Research*, **105**(A5), 10,343–10,352.

Staubach, P., Grün, E., & Jehn, R. 1997. The Meteoroid Environment Near Earth. *Advances in Space Research*, **19**(II), 301–308.

Witte, M., Rosenbauer, H., Banaszkiewicz, H., & Fahr, H. 1993. The Ulysses neutral gas experiment - Determination of the velocity and temperature of the interstellar neutral helium. *Advances in Space Res.*, **13**, (6)121–(6)130.